REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
11-07-05	Journal Article	

4. TITLE AND SUBTITLE	**5a. CONTRACT NUMBER**
Engineering Intersubband Nonlinearities in GaN/AlGaN Coupled Quantum Wells for Optimised Performance in Wide Bandwidth Applications	IN-HOUSE
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 61102F
6. AUTHOR(S)	**5d. PROJECT NUMBER** 2305
Richard A. Soref, Gregory Sun and Jacob B. Khurgin	**5e. TASK NUMBER** HC
	5f. WORK UNIT NUMBER 01
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
Electromagnetics Technology Division — Source Code: 437890 Sensors Directorate Air Force Research Laboratory 80 Scott Drive Hanscom AFB MA 01731-2909	AFRL-SN-HS
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-SN-HS-TP-2003-0661

12. DISTRIBUTION / AVAILABILITY STATEMENT
DISTRIBUTION A: APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED. CLEARANCE ESC-03-0661.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
We investigate nonlinear optical properties of coup led GaN/AlGaN quantum wells and show that one can engineer the response time and nonlinear phase shift within wide limits and thus achieve optimized performance for a given symbol rate.

15. SUBJECT TERMS
nonlinear optical properties, nonlinear phase shift, nonlinear devices

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Richard Soref
Unclassified	Unclassified	Unclassified	SAR	4	**19b. TELEPHONE NUMBER** *(include area code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Engineering Intersubband Nonlinearities in GaN/AlGaN Coupled Quantum Wells for Optimised Performance in Wide Bandwidth Applications

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Abstract: We investigate nonlinear optical properties of coup led GaN/AlGaN quantum wells and show that one can engineer the response time and nonlinear phase shift within wide limits and thus achieve optimised performance for a given symbol rate.

OCIS codes: (190.4360) Nonlinear optics, devices (190.4720) Optical nonlinearities of condensed matter

The progress in optical communications in the last decade was nothing short of spectacular – the data rates have increased from hundreds of MB/s to tens of GB/s and the number of channels has grown to hundreds. Further progress in the speed and complexity of optical networks is impeded by the necessity of optical-to-electrical conversion for switching and regeneration, thus the future networks must be all-optical ones. The crucial enabling elements of all-optical networking are the nonlinear optical devices used in switching, wavelength conversion, regeneration, etc.

Currently, all the nonlinear devices used in optical communications are based either on fiber nonlinearity [1] or nonlinearity of semiconductor optical amplifiers (SOA) [2]. Fiber nonlinearity is based on generation of virtual carriers and has a response time of less than a few fs, but the magnitude of the nonlinear refractive index is also very small ($<10^{16}$cm^2/W). The nonlinearity in the SOA is much stronger, but the response time is relatively slow (~100ps) which makes it inapplicable to rates faster than 10GB/s. The relation between the strength and the speed of the nonlinearity is rather obvious for the materials in which the nonlinearity has absorption saturation as its origin. For this type of nonlinear medium material, one can define a figure of merit as the power intensity required to produce 180 degrees of nonlinear phase shift in one absorption length, $I_\pi = \frac{\alpha\lambda}{2} n_2^{-1}$, where α is the absorption coefficient, λ is the wavelength in vacuum and n_2 is nonlinear refractive index. If the transition is broadened by Γ, the power intensity at a photon energy that is detuned from resonance by Γ, is given as $I_\pi = \frac{n}{\alpha_0} \frac{\Gamma}{z^2 \tau}$, where n is the refractive index, α_0 is the fine structure constant, z is the matrix element of the transition dipole, and τ is the response time that determines the maximum operational bandwidth. In this relation, τ can be used to minimize I_π. To maximize the nonlinearity for a given signal bandwidth B_{sig}, one should ideally set the response time in such a way that $\tau \sim B_{sig}^{-1}$. For the data rates of 40-160GB/s that means response times in the range of 5-20ps.

Unfortunately, there do not exist many nonlinear media wherein the relaxation rates can be easily adjusted in this range with the exception of intersubband transitions (IST) in quantum wells (QWs) where the intersubband relaxation rates are determined by the LO phonon scattering and strongly depend on the overlap of the wavefunctions that can be engineered within wide limits. For the last two decades, the IST could be observed only in the far-IR range, but more recently we have seen development of nitride-based semiconductors with large band offsets (deep wells) in which IST within the telecommunication window (1550nm) has been attained. Recently Iizuka et al [3] have measured intersubband absorption in GaN/AlN QWs in the 1.3-2.2μm range with relaxation times of 400fs, but this time is too short for the 40-160GB/s rates. An obvious way to increase the relaxation time is to use coupled QWs with reduced overlap of wavefunctions involved in the transition. Unfortunately the reduction in overlap also decreases the transition matrix element and thus does not improve figure of merit.

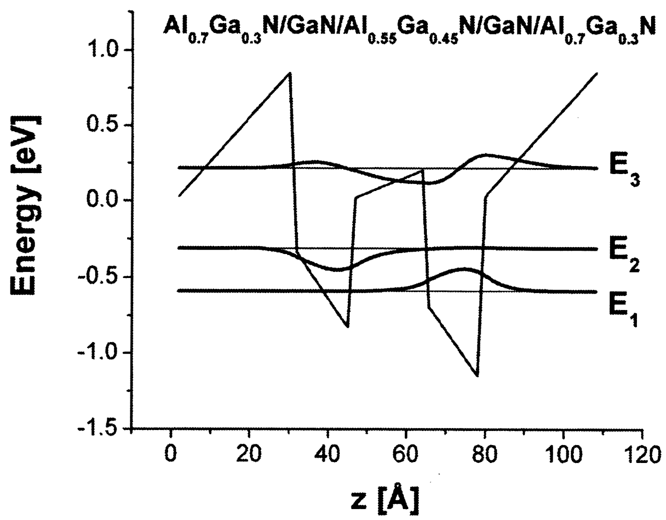

Fig.1. A three-level system consisting of $Al_{0.7}Ga_{0.3}N$ barriers confining two coupled GaN QWs (15Å) separated by a $Al_{0.55}Ga_{0.45}N$ barrier (20Å). The there levels are located at E_1=-0.588eV, E_2=-0.313eV, and E_3=0.216eV.

In order to optimize the relaxation rate and the IST strength separately we propose to use a three-level coupled QW system as shown in Fig.1. IST takes place between the ground state 1 and excited state 3 while the state 2 serves as a trap delaying relaxation to the ground state. Solving balance equations one can obtain the expression for the effective relaxation time, $\tau = \frac{\tau_{31}(2\tau_{32}+\tau_{21})}{\tau_{31}+\tau_{32}}$. For $\tau_{31} \approx \tau_{32} << \tau_{21}$ we obtain $\tau \approx 0.5\tau_{21}$. The effective relaxation time can be varied within wide limits by changing the central coupling AlGaN barrier width, while the IST strength and wavelength are maintained by small changes in the barrier Al composition. In Fig.2 we show the results of calculations of the response time and nonlinear switching power. As the barrier width changes in the range of 1-2 nm, one can see that the effective relaxation time changes from 0.4 to 5 ps. For a typical RZ signal these values correspond to the bit rates range of 40-640 GB/s. The nonlinear switching power densities of <10^8 W/cm^2 correspond to switching instant powers in the <1W range in a typical waveguide - substantially less than in a fiber loop. With the doping density of 5×10^{17}/cm^3 the switching length would be only ~100μm compared to the meters required in a fiber loop.

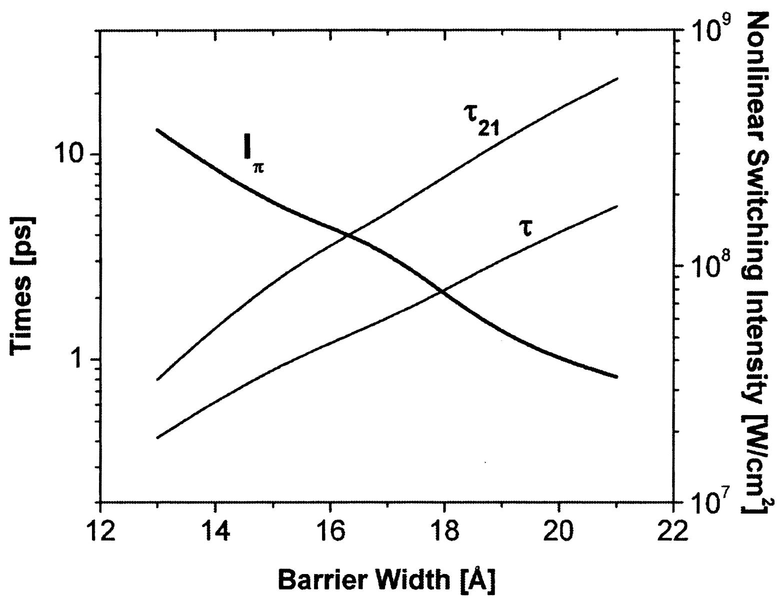

Fig.2. 2→1 Scattering lifetime (τ_{21}), effective relaxation time (τ), and nonlinear switching intensity as a function of coupling barrier width

In conclusion, we have shown that GaN/AlGaN coupled QWs with a trap state provide unique opportunity for engineering bandwidth-optimized all optical devices with low switching power.

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